Simulation Study of COSMIC — A Compton Telescope All-Sky Monitor Concept for Low-Energy Gamma-Ray Astronomy

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Abstract

The highly transient nature of cosmic low-energy gamma-ray sources offers unique insight into the astrophysics of extreme processes. Sensitive, long-term, all-sky monitoring is required to make sense of the variable emission. Instrumentation for such observations must have the combination of large effective collection area, wide field-of-view and good angular resolution. Recent advances in position-sensitive detectors and associated electronics make it possible to consider a multi-scatter Compton telescope, combined with a coded mask, as an all-sky monitor in the energy range ~10 keV to a few MeV. We present simulations of various configurations of such an instrument and show that it can provide a substantial improvement over other sky monitor strategies in this energy regime.

I. INTRODUCTION

Recent observations of the low-energy gamma-ray sky obtained with instruments on the *Compton Observatory* (CGRO) and GRANAT have provided a wealth of data on a variety of interesting galactic and extragalactic phenomena, including X-ray binaries, pulsars, soft gamma-ray repeaters, active galaxies and gamma-ray bursts (GRBs). The CGRO Burst and Transient Source Experiment (BATSE [1]) has been particularly successful because its large area and all-sky coverage allow it to monitor even the most highly variable sources. Next-generation instrumentation requires a combination of wide field-of-view, good angular resolution and significantly better sensitivity than BATSE. Various instruments have been proposed that excel in one or two of these requirements, but few accomplish all three in this energy range.

In a previous paper [2], we proposed that an instrument using the Compton telescope technique would be a logical follow-on to BATSE—providing significantly better sensitivity and location accuracy while maintaining a large field-of-view. Here, we enhance the general concept of a Compton telescope all-sky monitor for low-energy gamma rays with detailed Monte Carlo simulations of various instrument configurations and detector parameters.

II. INSTRUMENT CONCEPT

The Compton telescope technique is well known and has been successfully exploited for medium energy gamma rays—most notably by the CGRO COMPTEL (0.75–30 MeV)

instrument [3]. The typical design uses two arrays of detectors: one of relatively low atomic number (D1), in which incident photons in the energy range of interest interact primarily via Compton scattering, transferring part of their energy, and a second array (D2) of relatively high atomic number, in which the scattered photon ideally is totally absorbed. The kinematics of Compton scattering, combined with measurements of the interaction locations and energies, constrain the direction of the incident gamma-ray to lie within an annulus. Tracking of the scattered electron in the first layer could, in principle, limit the photon direction more unambiguously, but this is technically difficult at energies below a few MeV [4].

Extension of a Compton telescope to lower energies (e.g., 50 keV to 1 MeV, where gamma-ray bursts are most fluent) requires excellent energy resolution (approaching 0.1 keV and 1 keV in D1 and D2, respectively), good position resolution (~1 mm) and the ability to utilize multiply scattered photons and large-angle scatters (the traditional Compton telescope only utilizes photons that singly scatter in D1 at small angles ≲45°). In our earlier work [2], we noted that current semiconductor detector technology comes interestingly close to meeting these requirements. However, since intrinsic atomic electron
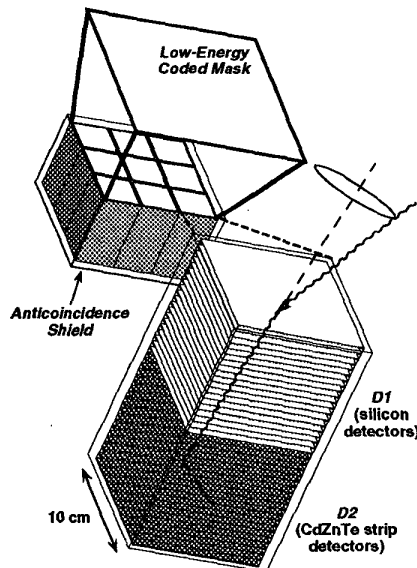

Figure 1: Schematic illustration of the modular COSMIC instrument configuration showing the interaction of a photon within a detector module.

binding effects dominate the Compton scattering response below ~100 keV (also known as "Doppler broadening"), an alternative detection technique at low energies is desirable.

The instrument we envision (the COmpton Sky Monitor with Imaging and Calorimetry or COSMIC) uses several thin layers of silicon detectors (either micro-strip or pixillated) as D1 scatterers and several thin layers of CdZnTe (CZT) detectors as D2 absorbers (Figure 1). Because this design incorporates many scattering layers, we are able to make efficient use of multiple as well as single Compton scatter events. This capability improves the overall detection efficiency over a wide energy range and allows for a much wider field-of-view (FoV) than previous Compton telescopes. A coded mask, used in conjunction with the upper Si detector, would be optimized for the energy range 10–100 keV, where Doppler broadening and a decreasing Compton cross-section limit the effectiveness of the Compton telescope technique. In the following sections, we describe simulations of the Compton telescope response of COSMIC, independent of the coded mask (i.e., assuming that a thin mask would be essentially transparent above ~100 keV).

III. SIMULATIONS

The capabilities and performance of various COSMIC instrument configurations are being studied with a modified version of the GEANT Monte Carlo detector simulation package [5]. The modifications provide a more accurate treatment of the Rayleigh and Compton scattering processes— particularly including important Doppler broadening effects [6]. The modified GEANT is used to track primary photons and secondary photons and electrons through a three-dimensional model of the COSMIC instrument over a broad energy range from 1 keV to 100 MeV.

A. Baseline COSMIC Simulation Model

After studying several different instrument configurations we have chosen a modular baseline design. Each module consists of 40 semiconductor detectors (10 cm × 10 cm × 1 mm), arranged in a stack with 0.5 cm spacing. The upper 20 detectors (D1) are silicon, while the lower 20 detectors (D2) are CZT (see Figure 1). The overall detector material thus consists of 2 cm thick Si and 2 cm thick CZT. By using stacks of thin detectors, rather than two thick detectors, we can accurately determine interaction locations in all three dimensions. For the simulation model, each layer is 10 cm × 10 cm in area, which in practice may be realized with a planar array of smaller detectors (at the cost of more dead space).

Space between the detector layers and the arrangement of modules affects the angular resolution, energy resolution, sensitive energy range and FoV of the instrument. In this paper, we mainly consider two instrument configurations: planar arrays of 3 × 3 modules (30 cm ×30 cm detector area) and 10 × 10 modules (100 cm ×100 cm detector area). A 1 cm gap surrounds the sides of each module in an array. This gap is made of a material designed to simulate a passive mass of generic electronics (a mixture of O, Al, Si, Fe, Cu, Sn and Pb) and wiring on the edges of the detector layers.

An important feature of the COSMIC simulations is that the modules are not independent. Photons are allowed to interact in the detectors from any of the modules. The entire instrument array is surrounded by a 0.25 cm thick plastic charged particle anti-coincidence shield.

To account for the non-ideal measurement errors of real detectors in our simulations, we broaden the energy and interaction locations about their ideal values according to a Gaussian distribution and apply realistic thresholds. Detector broadening parameters were chosen to yield acceptable instrument performance while being technically attainable in the foreseeable future. Interaction positions are blurred in all directions with a standard deviation $\sigma_r = 0.5$ mm, but are not allowed to exceed the physical bounds of the detector where the interaction took place. Energy deposits E in the detectors are subjected to the thresholds $E_{D1} > 0.5$ keV and $E_{D2} > 5$ keV and broadened according to

$$\sigma(E) = \sqrt{A^2 + B^2\,(E/100\,\text{keV})}. \qquad (1)$$

The energy resolution parameters A and B account for electronics noise (A) and statistical measurement resolution (B). We take (A, B) to be $(0.1, 0.25)$ and $(0.5, 1.0)$ in D1 and D2, respectively (in keV). Events depositing >300 keV (i.e., minimum-ionizing) in the anticoincidence detector are rejected.

B. Multiple Compton Scatter Event Reconstruction

Algorithms for reconstructing multiple scatter events have been described by several researchers [7, 8, 9]. We have applied elements of these techniques to the COSMIC simulation program in order to reconstruct (if possible) the incident direction of each photon regardless of the number of scatters or the number of detector layers involved in the interactions. Briefly, each COSMIC "event" consists of a set of "hits", where each hit represents the successful measurement of an energy deposit and an interaction location. For singly scattered photons, there are two hits, for double scatters, three hits and so on (assuming total energy absorption). The goal of the reconstruction algorithm is to identify the proper sequence of hits. Once this is known, the incident photon direction is determined using the first two hits as in the standard Compton telescope. In our reconstruction algorithm, the best hit sequence is taken to be that with the minimum RMS deviation between kinematic scatter angles (computed from energy deposits using the Compton formula) and scatter angles determined from hit locations at each scatter in the sequence. In the case of an event with only two hits, this method is not possible, so the sequence with the maximum probability based on the Klein-Nishina formula is used.

Some events cannot be reconstructed. At low energies ($\lesssim 200$ keV), this is due to intrinsic Doppler broadening of the scattered photon energies and the relatively poor resolution of the small energy deposits, while at high energies ($\gtrsim 2$ MeV) non-Compton scatters (i.e., pair production, electron scattering, etc.) and escaping energy confuse the true interaction sequence. Our reconstruction algorithm is between 80%–99% efficient, depending on energy.

C. Basic Performance

To examine the basic detection properties of COSMIC, we simulate a point source of gamma rays with a plane-parallel beam of incident photons extending over the full instrument model (photons coming from the sides *are* valid). For each photon event, the broadened hit parameters are subject to the event reconstruction algorithm described above. A successfully reconstructed event yields the total energy deposit (E_{tot}), the kinematic scatter angle ($\bar{\varphi}$) and the scatter direction vector (the vector along the direction of the first two hit locations; see Figure 1).
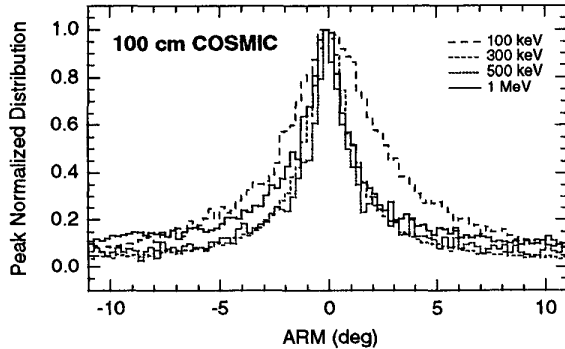

Figure 2: Normal incidence angular response function at four energies.
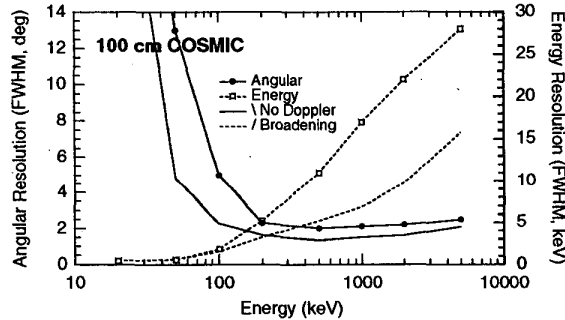

Figure 3: Angular resolution and photopeak energy resolution at normal incidence with and without Doppler broadening.

The difference between $\bar{\varphi}$ and the angle from the scatter direction vector to the known (or trial) source direction gives the *angular resolution measure* (ARM). The distribution of ARM for a source at normal incidence is shown in Figure 2 and the ARM FWHM as a function of energy is plotted in Figure 3. At energies $\lesssim 200$ keV, the angular resolution is dominated by Doppler broadening and the energy resolution in D1, while at higher energies the D2 energy resolution and the position resolution in both D1 and D2 become the more important factors. The actual source location accuracy will, of course, be much better than this because it depends on the error in the centroid of the ARM distribution, and not its width. We estimate that strong GRBs could be localized to better than 30'.

The total energy resolution of the instrument depends not only on the D1, D2 energy deposit broadening parameters used in the simulations, but also on the distribution of scatter angles, which in turn is affected by Doppler broadening and the accuracy of the event reconstruction algorithm. As shown in Figure 3, COSMIC offers excellent energy resolution over a broad range, making it an attractive possibility for nuclear line studies.
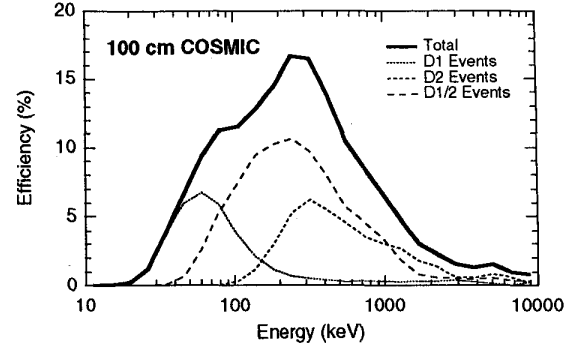

Figure 4: Detection efficiency for a point source at normal incidence. Events are required to reconstruct to the proper source direction ($|ARM| < 1 \times FWHM(E)$).
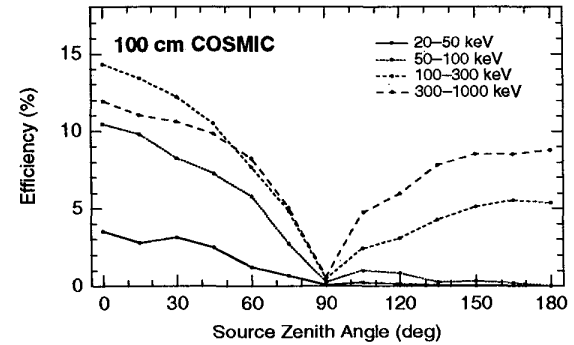

Figure 5: Detection efficiency as a function of viewing (zenith) angle in four energy bands (ARM selected).

Shown in Figure 4 is the detection efficiency (ratio of effective detection area to detector area) at normal incidence as a function of energy for all events with $|ARM| < 1 \times FWHM(E)$. These correctly identified events determine the sensitivity of the instrument since other, "off-diagonal", events are more easily confused with background. The COSMIC efficiency below 80 keV and above 1 MeV is dominated by photons that scatter solely the D1 and D2 layers, respectively. At intermediate energies, photons that interact in the D1 *and* D2 layers are the most important. Above 500 keV, multiple scatters dominate—comprising 50%–90% of the various event types—whereas single scatters are more important at lower energies. Including all the different event types yields greater than 5% efficiency over a wide energy range extending from 40 keV to 1.5 MeV. However, it is important to note that the sensitivity will be poor below ~100 keV due to the poor angular resolution (and thus poor background suppression) at low energies. As shown in Figure 5, the detection efficiency of COSMIC degrades slowly out to a zenith angle of 60°, producing a wide FoV. Efficiency is poor around 90°, where only the edges of the detector layers

are exposed. At energies >100 keV, COSMIC is also efficient at detecting photons from behind the instrument, as the CZT becomes the domninant scattering medium.   In an actual instrument, this property could be used to reject a large fraction of background photons from the earth albedo.

The angular resolution, energy resolution and efficiency of the 30 cm configuration are comparable to that of the 100 cm instrument. The major difference is the decreased effective area of the smaller telescope. The FoV of the smaller instrument is also ~10% narrower due to the decreased ratio of detector area to module height.

D. Estimated Sensitivity

To compare the sensitivity of COSMIC to current instruments in the same energy range we have also simulated a simple estimate of the background expected for a satellite in low Earth orbit. This background estimate consists of two components: 1) The isotropically distributed diffuse cosmic gamma-ray flux, modeled with three power laws [10] and 2) An internal background based on balloon flight CZT measurements from 20 keV to 1 MeV [11]. For the diffuse flux component, we performed direct simulations of isotropically distributed photons, propagated through the instrument model and subject to event reconstruction. Only those background events that could be confused with source photons will affect the instrument sensitivity. Thus, in our background estimate we only include diffuse flux events that are within a 1-FWHM ARM window around the source position. This use of photon direction information effectively reduces the diffuse flux count-rate by a factor of 50%–99% (energy dependent; >95% above 100 keV)—indicating the advantage of a Compton telescope system. The diffuse flux simulations include photons from all directions, so that Earth background is partially modeled. However, we do not account for the stronger flux from the Earth's limb. In practice, Earth albedo background could be greatly reduced through data selections and/or shielding. For the internal background, we did not perform detailed simulations, but rather scaled the balloon measurements to the COSMIC detector volume (for the Si detectors, CZT count rates were scaled by density) in the cosmic ray environment of a low Earth orbit [10]. Whatever their origin, internal background events will have a smooth angular distribution, making it possible to distinguish a large fraction of them from source photons.   In our model, we reduce the internal background count-rate by the same (energy dependent) factor as that found in the isotropic simulations. The largest uncertainty in the internal background is at energies >1 MeV, where no measurements exist. To be conservative, we extrapolate the balloon CZT spectrum with a hard $E^{-0.5}$ power-law above 500 keV.

At energies ≲400 keV, the background is primarily the cosmic diffuse flux, with the internal background dominating at higher energies. Our sensitivity estimates above ~400 keV are thus crucially dependent on what we assume for the internal background. Parsons et al. [11] speculated that (n,γ) reactions might dominate the CZT internal background, given

the large neutron cross-sections of cadmium isotopes. With COSMIC, we will be able to suppress these events based on their reconstructed direction information. Since the bulk of internal events will originate in the D2 CZT layers, they will have a unique signature, and reduction may be even more than the factor we assumed.
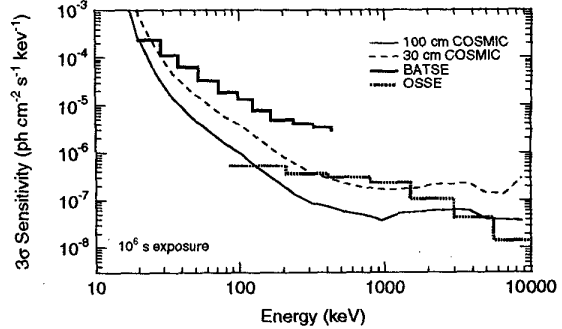

Figure 6: Estimated normal incidence point source sensitivity for a long duration observation.
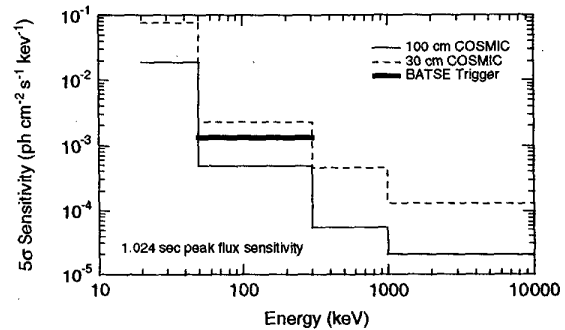

Figure 7: Estimated normal incidence sensitivity to gamma-ray bursts.

Figures 6–7 illustrate the sensitivity of COSMIC to a point source at normal incidence for long-duration observations and for gamma-ray bursts. As discussed above, the source and background simulations used for the sensitivity estimates were each subject to ARM selection, since in this region the source and background response signatures are easiest to distinguish. In practice, use of the full instrument response function (i.e., including the tails) will improve the sensitivity, as will more creative selections on the event parameters designed to optimize the signal-to-noise ratio. As the figures indicate, a large (1 m^2) version of COSMIC could provide true imaging with sensitivity better than CGRO OSSE [12] over a wide FoV and would offer GRB sensitivity a factor of ~3 better than BATSE [1]. A smaller 30 cm instrument could have 1-day sky-monitoring capability comparable to that of BATSE, with somewhat poorer sensitivity to bursts.

IV. DISCUSSION

Simulations indicate that COSMIC could, in principle, be a capable all-sky monitor and gamma-ray burst detector. With the straightforward addition of a low-energy coded mask, it would provide sensitivity, location accuracy, energy

resolution and polarimetry that are significant improvements over current instruments. The flexible COSMIC design offers many valuable possibilities, including configurations that are more optimized for all-sky (i.e., non-occulted) coverage. An example using 96 of the basic modules is shown in Figure 8. This configuration provides angular resolution, energy resolution and on-axis sensitivity comparable (within 10–30%, depending on energy) to the 100 cm × 100 cm planar design, with significantly improved off-axis sensitivity due to the canted geometry. Another option is to optimize some of the coded mask modules (e.g., above the central detectors) for arc-minute localization of selected sources over a restricted FoV.
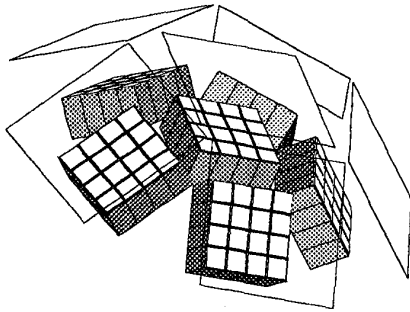

Figure 8: COSMIC all-sky coverage instrument configuration.

Realizing the COSMIC instrument concept with available detectors is an obvious challenge. Large-area silicon and CZT detectors have not yet achieved the energy resolution used in our simulations. However, the simulation parameters are somewhat overly restrictive in that reasonable instrument performance is obtained with significantly worse energy resolution. For instance, increasing the D2 energy resolution noise term (A in eqn 1) from 0.5 keV to 2.5 keV (1σ) only degrades the angular resolution and sensitivity by $\lesssim 20\%$. The effect of energy resolution in D1 is more severe, where increasing the silicon noise level from 0.1 keV to 0.5 keV (1σ) degrades the angular resolution and sensitivity by $\sim 50\%$ below 200 keV. However, the performance at low energies is compensated by the use of a coded mask system whose sensitivity and angular resolution do not depend strongly on energy resolution. It thus appears that an instrument like COSMIC is feasible in the foreseeable future. We will therefore continue to refine our design, concentrating in particular on the unexplored aspects of polarimetry response and coded mask design.

VI. REFERENCES

[1] Fishman, G. J., et al. "The Burst and Transient Source Experiment (BATSE) scientific objectives and capabilities," *Proc. of the GRO Science Workshop, Greenbelt, MD*, pp. 3-47, 1989.

[2] Paciesas W. S., et al. "Improved gamma-ray burst detector using a Compton telescope technique," *SPIE Proc.*, vol. 2806, pp. 606, 1996.

[3] Schönfelder, V., et al. "Instrument description and performance of the imaging gamma-ray telescope COMPTEL aboard the Compton Gamma-Ray Observatory," *Astrophys. J. Suppl. Ser.*, vol. 86, pp. 629, 1993.

[4] Tümer, O. T., et al. "The TIGRE instrument for 0.3–100 MeV gamma-ray astronomy," *IEEE Trans. Nucl. Sci.*, vol. 42, no. 4, pp. 907, 1995.

[5] CERN Program Library Long Writeup W5013. "GEANT–detector description and simulation tool," *Geneva: CERN*, 1993.

[6] Namito, Y., Ban, S. & Hirayama, H. "Implementation of the Doppler broadening of a Compton-scattered photon into the EGS4 code," *Nucl. Inst. Meth. in Phys. Res. A*, vol. A349, pp. 489, 1994.

[7] Kamae, T., Enomoto, R. & Hanada, N. "A new method to measure energy, direction and polarization of gamma rays," *Nucl. Inst. Meth. in Phys. Res. A*, vol. A260, pp. 254, 1987.

[8] Kamae, T., Hanada, N. & Enomoto, R. "Prototype design of multiple Compton gamma-ray camera," *IEEE Trans. Nucl. Sci.*, vol. 35, no. 1, pp. 352, 1988.

[9] Aprile, E., Bolotnikov, A., Chen, D. & Mukherjee, R. "A Monte Carlo analysis of the liquid xenon TPC as a gamma-ray detector," *Nucl. Inst. Meth. in Phys. Res. A*, vol. A327, pp. 216, 1993.

[10] Gehrels, N. "Instrumental background in gamma-ray spectrometers flown in low Earth orbit," *Nucl. Inst. Meth. in Phys. Res. A*, vol. A313, pp. 513, 1992.

[11] Parsons A., et al. "CdZnTe background measurements at balloon altitudes," *SPIE Proc.*, vol. 2806, pp. 432, 1996.

[12] Kurfess, J. D., et al. "Scientific objectives of the Oriented Scintillation Spectrometer Experiment," *Proc. of the GRO Science Workshop, Greenbelt, MD*, pp. 3-35, 1989.